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C² INFORMATION MANAGEMENT:
DATA FUSION AND TRACK ID's
IN A MULTIPLE SENSOR ENVIRONMENT

by

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C^2 Information Management: Data Fusion and Track ID's in a Multiple Sensor Environment

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ABSTRACT

Battle management decision making requires a composite picture of the environment, including identification of moving and stationary "targets". The current state of technology allows large volumes of data to be gathered from multiple sources. Target kinematics and identity features must be derived through fusion of the data. Initial assignment and maintenance of track numbers, the identifying labels, may lead to ambiguity in command and control information management. The problem is discussed in terms of data fusion in a multiple sensor environment, giving particular emphasis to managing track ID numbers in representative architectures. An overview of data fusion provides a framework for the problem of track ID's. A Centralized Architecture, Distributed Architecture, and two Hybrid Architectures are developed focusing on design tradeoffs. System evaluation using the Analytic Hierarchy Process furnishes the reader an illustration of a process which might be used to select an optimal architecture. This research does not attempt to propose a specific design, but identifies several key criteria which must be evaluated and suggests a framework for comparative analysis.

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I. INTRODUCTION

Information management is critical to the command and control of today's fighting forces. Doctrine must be cunning and state of the art technology integrated, to meet the challenge of the future. In the environment of real time weapons control, sensor information must be processed with the same speed. The decision-maker is faced with the requirement for almost instantaneous processing of high volume data. This environment demands an organizational and architectural structure that will enhance automation of decision processing. The Component Warfare Concept provides organizational structure which supports integration of information (data fusion) from all sources. An architecture must be designed which will allow implementation of automation for the data fusion and decision processing. Techniques for comparative analysis must be identified, as well as measures of performance, to enhance selection of the optimal design.

II. MISSION AND ORGANIZATION OF C^2

Command and control - The exercise of authority and direction by a properly designated commander over assigned forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission. [REF 1:p. 77]

A. HISTORICAL PERSPECTIVE

The ability to correlate raw data, build an assessment and form a response based on interpretation and abstraction of the situation has always been a key to warfighting success. In the days of Sun Tzu, the task could probably be carried out by a single warrior. One man could assimilate and evaluate all of the available intelligence information about the enemy, and form a response strategy. As the technology of war changed, and the size of the arena, the task of managing the growing volume of information demanded complex intelligence gathering and analysis staffs.

The modus operandi of the fighting man changed too, primarily in the role of leadership. Centralized organization of large forces required more information to flow out, from that point of control, to the forces. While in theory, commanders at the lowest echelon are expected to make decisions and execute their appropriate mission, modern history suggests that tactical decisions of any real importance are made at the highest level (sometimes by the commander-in-chief) and communicated down to the lower echelon for execution. While this may not be the most efficient method of command and control (in terms of the delay in information relay up and down the chain of command, and the inevitable distortion of detail and intent caused by filtering that naturally occurs in the communication process), it has in recent history proven effective (in terms of successful completion of the assigned missions, and as an "extension of politics", in clear execution of foreign policy objectives of the President).

B. NAVAL THREAT ENVIRONMENT

The Navy, perhaps, is more sensitive to the degree of centralized command and control, due to the nature of day to day operations. Far from the commander-in-chief for extended periods of time, naval commanders are forced to operate with a certain amount of tactical autonomy. This is not to say that the wheel is reinvented each time a decision is made, since tactics are developed for numerous scenarios by eschelons higher than the deploying commander prior to departure on a mission. Scenario development is not all inclusive, however, and the deployed commander cannot call home for assistance on every decision that does not match the template provided. The Navy, as a general rule, regards the on-scene commander as the person able to make the best tactical decision.

Warfare technology today places the carrier battle group commander in a precarious position. On the one hand, he has far more information instantly available than ever before, but the sophistication of the potential threat has at least kept pace. No longer is he given the leisure of manually analyzing each piece of raw data, hypothesizing about the capabilities and intentions of the enemy, and finally making a decision in response to a threat. Tactics provide a substitute for information processing in a real time environment. The decision maker simply has to look for predetermined clues as indicators of designated threats. Upon detection of a threat, a predetermined response is executed.

Threats come in a variety of forms, and while detected characteristics may not be exclusive to a single target type, much can be determined when information from various sources is fused. Subsurface threats can be generally characterized as slow, but covert. Location becomes the key, since identification as a submarine is relatively straight-forward, once the target is acquired. The surface target is generally slow, and overt. The tactical threat is not in being boarded, but rather in the power projection capability of the ship's weapons (lethality and range). The danger of an air target is generally in the small size and high speed of the craft. Sensors must have revisit rates that are high enough to "catch" the moving vehicle.

The commander must be attentive to all events which may require the intervention of the battle group, but especially targets within his operating area. Typically the number of surface and sub-surface vessels in that area would be less than 200. The nature of such activity is slow with at most 5 command and control decisions per minute required. With target state changing so slowly, only 5000 reports/minute would be received. If this were the extent of the environment, the impact on data management would be minimal. [REF 2:pp. 50-57]

Several scenarios have been hypothesized over the years in development of naval tactics. The case which requires the most intense management of information is an all out air/sub/surface battle between two carrier battle groups. Of critical interest in this environment are air targets. Within a 500 mile radius, the battle group might encounter 1000 targets simultaneously. It would be required to process them in real time due to the speed of each vehicle. Fifty command and control decisions might be required of the commander in a minute. Because of the speed of the potential threats, up to 100,000 reports per minute might be required to accurately track, identify, and target the threats. [REF 2:pp. 50-57]

The other naval battle environment is the low intensity conflict. It is characterized as low in intensity, because of the lower level of power projection, and it generally occurs in littoral waters rather than far out at sea. This results in the requirement to manage a significant amount of collateral information, that while not pertinent to the execution of the tactical mission, is paramount in the "extension of politics" strategy and national security objectives.

Decision making in the environment of either a full scale war or the low intensity conflict requires efficient decision processing. To enhance the fusion of information that is available to the deployed commander, the Navy utilizes an organizational structure that modularizes information processing by warfare areas.

C. COMPOSITE WARFARE CONCEPT

The simultaneous operation of naval forces in all media requires a command and control structure designed to manage all levels of conflict in all environments. The Composite Warfare Command structure was developed to meet this need. Warfare areas are distinguished by the media in which they are carried out and type of mission. The power projection mission of the Navy is accomplished using specially designated assets to execute Amphibious Warfare (AMW), Naval Special Warfare (NSW), and Strike Warfare (STW). These warfare missions are offensive in nature and generally beyond the scope of this research. The three primary missions in sea control are Anti-Air Warfare, Anti-Submarine Warfare, and Anti-Surface Warfare.

1. Anti-Air Warfare (AAW)

The goal of Anti-Air Warfare is to destroy or neutralize enemy air platforms including missiles. This is accomplished with fighters, anti-aircraft guns, surface-to-air missiles, anti-air missiles, and electronic countermeasures. Tactics cover the entire spectrum, from operations in general war on the open ocean, to low intensity conflict in littoral areas.

The layered employment of various platforms provides an outer defense perimeter several hundred miles out from the battle group commander. The area defense zone extends to the range of an anti-ship cruise missile, and the immediate vicinity of the ship is the local defense zone. Each area has weapons and tactics designed for employment should a threat reach it.

Support comes from shore facilities, as well as afloat, for indication and warning, threat assessment, collection and distribution of air tracking and targeting (critical for engagement planning and queuing of weapons systems) as well as battlefield damage assessment. [REF 1:pp. 29-31, REF 3:pp. 11 & 39-43]

2. Anti-Submarine Warfare (ASW)

The goal of ASW is to deny the enemy the use of his submarines. This is accomplished in the forward area, near the enemy's shores, by our own attack submarines. Along barriers, and for regional control, airborne ASW platforms operate with the support of national systems. The battle group relies on its own platforms for self-defense. These include, frigates, S-3 Viking ASW aircraft, LAMPS helicopters, and submarines. Essential to this mission is the exchange of information on a high-capacity, secure, jam resistant, unexploitable communications network. [REF 1:pp. 29-31, REF 3:pp. 11 & 39-43]

3. Anti-Surface Warfare (ASUW)

The traditional role of the surface vessel is to destroy or at least reduce surface threats. This is achieved using anti-ship cruise missiles, naval gunfire, torpedoes, and electronic countermeasures. [REF 1:pp. 29-31, REF 3:pp. 11 & 39-43]

III. MANAGEMENT OF INFORMATION IN C^2

The battle group commander operates in a huge arena. Volumes of information are fed to him from sources such as shore intelligence facilities, airborne and space surveillance systems, local sensors within the battle group and sensors organic to his command vessel. The area of interest to him and the kind of information desired depends on the decisions he is attempting to answer at the moment.

A. HISTORICAL BACKGROUND

Several problems must be addressed in an analysis of the environment in which the battle group commander must make decisions. First, the available volume of data that must be processed is huge. Processing must very quick in order to give the commander enough time to make decisions. Second, data is arriving from many diverse and geographically separate sources. The commander must have some means of associating and correlating information from disparate sources to get a composite picture of the situation he faces.

In spite of the fact that the concepts of data fusion has been around for years, the results of formalizing its definition and taxonomy are a more recent product of the Data Fusion Subpanel of the Joint Director of Laboratories Technology Panel for Command, Control and Communications, which was established in 1984. The objective of the Data Fusion Subpanel is to improve the coordination of individual Service Data Fusion Research and Development programs through the exchange of technical information and concepts, by initiating new multi-Service cooperative research programs and technology demonstrations. [REF 4:p. 1]

The taxonomy of data fusion, Figure 1, is a description of the very processes that make up the nucleus of modern warfighting. It clearly is not an end to itself, but rather the lubricant of real time response. It does not occur in only one place or time, but rather throughout the process from acquisition to and including response, Figure 2.

B. INFORMATION IN THE TACTICAL ENVIRONMENT

Information can be categorized as organic or nonorganic. Generally, organic information is obtained from sources integral to a platform. The raw data requires processing on site to be useable. Nonorganic information is received from sources detached from the platform. The data has been processed by another platform prior to dissemination. Nonorganic information may assist in tactical decisions or it may provide strategic direction to the commander.

Geopolitical and intelligence data is an example of nonorganic, which while seemingly extraneous, plays an important role in setting the stage for an accurate situation and threat assessment. This backdrop contributes to the mindset that leadership develops upon entering the theater of operations. It is important that the background information not lead to faulty conclusions in dealing with actual events in theater, but rather support a contemplative analysis of possible scenarios which could occur.

Data most relevant for real time decision making is received from sources organic to the platform or at least organic to the theater. Movement of air, surface and

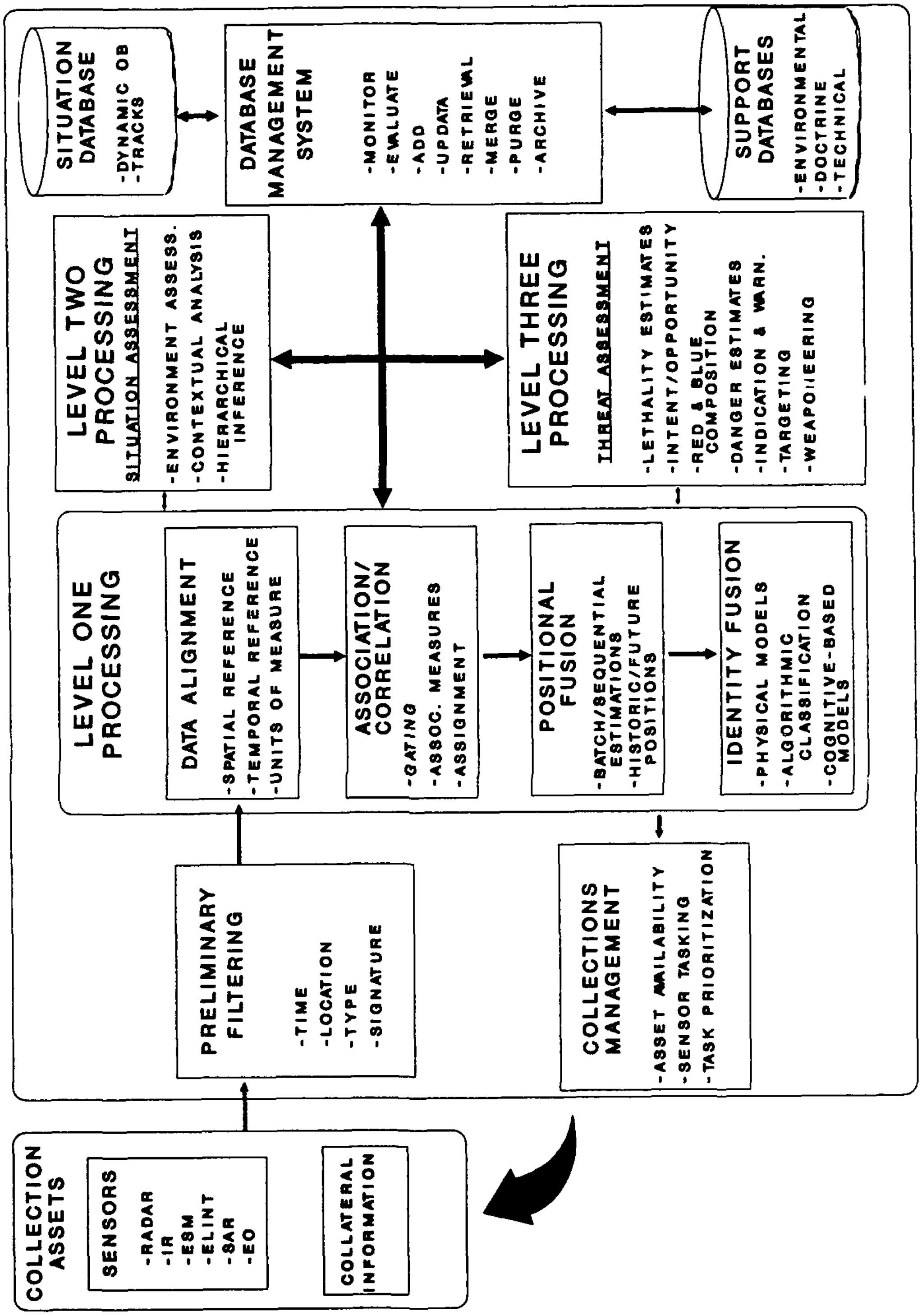

Figure 1
TAXONOMY AND PROCESSES OF DATA FUSION [Source: REF 2:p. 16]

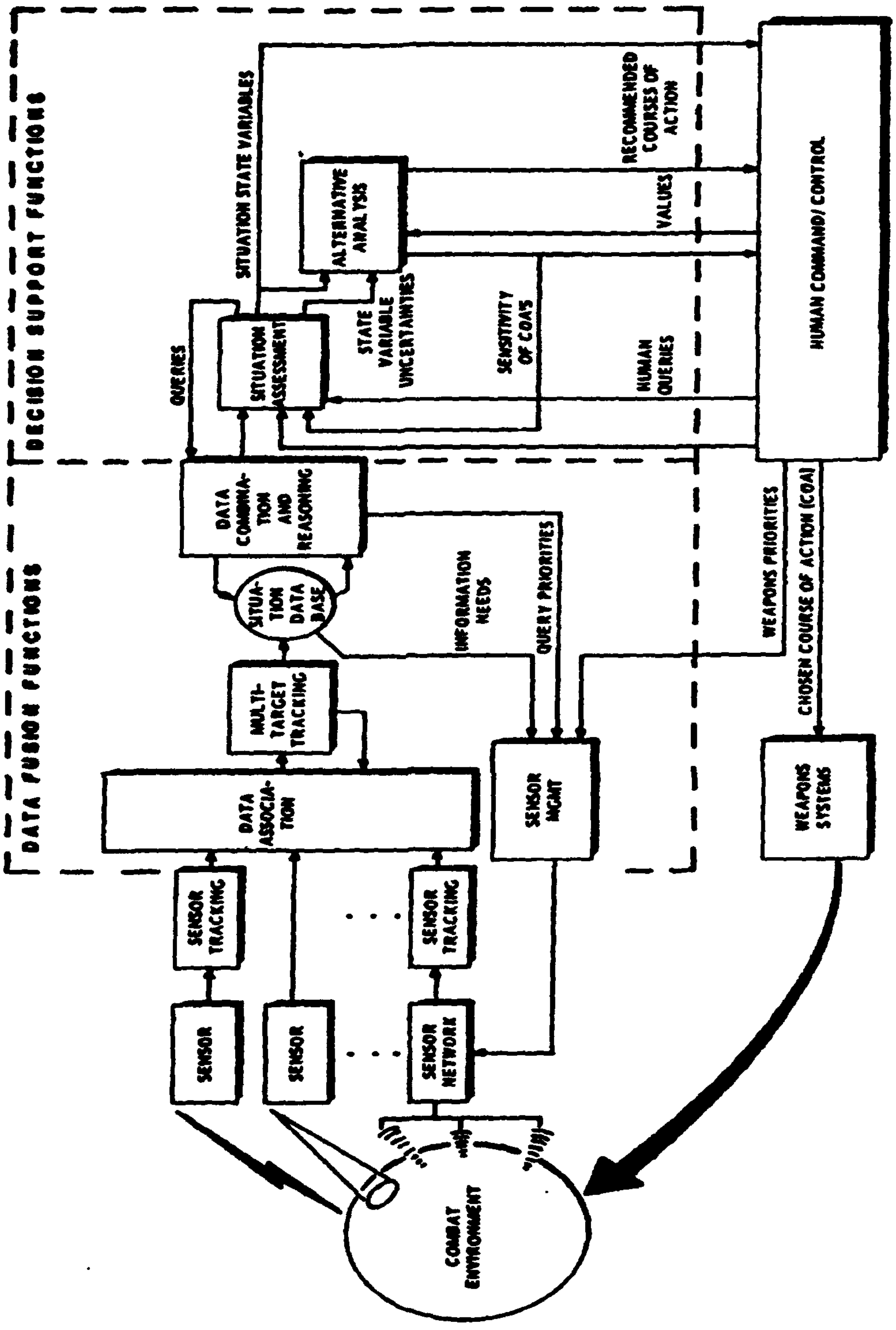

Figure 2
GENERALIZED FUSION ENVIRONMENT [Source: REF 2:p. 62]

subsurface targets (military and civilian), generates contact data from multiple sensors. The information must be analyzed together to eliminate redundancy and to provide the added value of multiple perspective sensors.

C. DATA FUSION

The problem of fusing target data is primarily one of managing speed. If the decision maker had a long period of time to evaluate track data, the probability of analysis error would be much smaller than in the environment of real time decision making. A missile approaching in a covert mode will allow the decision maker very little time to respond once acquisition occurs. The mathematical, statistical and inferential processes that take place in data fusion are divided into three levels. At the lowest most algorithmic level (LEVEL ONE) occur the manipulation of raw sensor data and tracks. This includes adaptive signal processing resulting in detection, normalization of data in terms of a three dimensional position and time (sometimes called alignment), one of several methods to associate detections in order to perform tracking, employment of one of several algorithms to correlate and fuse tracks from nonorganic sensors with tracks from organic sensors, and target identification. [REF. 2:pp. 15-19]

LEVEL TWO (Situation Assessment) and LEVEL THREE (Threat Assessment) require more reasoning and are hence less algorithmic. These are the decisions of strategy and tactics of war. Throughout the centuries men have devised methods for waging war that required knowledge of the enemy. From deception advocated by Sun Tzu to maneuver as executed by German Panzer Divisions in North Africa, the decision maker's knowledge of enemy movement and capabilities played a major role in warfighting success. Assessment is not a purely mathematical process, but rather, requires multiple perspective spatial views of the environment, and a doctrine to guide establishment of goals or objectives. Fusion is not the focus in assessment, but the fused product is critical in assessing the enemy. The decision maker at this level must evaluate the composite picture, consider the mission or goals that are to be accomplished and generate hypotheses for each target as well as for the whole force.

To support this decision-making, large databases must be maintained including Threat Capabilities, Own Force Capabilities, Mission Goals, Strategic Intelligence, Behavior-Doctrine of Enemy and Own Force, Terrain Mapping (applicable in a power projection mission), and Airways Mapping. Quantitative estimation is performed along with sensor and weapons modeling. Perspectives of and relationships between platforms are analyzed resulting in a recommendation. [REF 2:pp. 263-291]

IV. DATA FUSION - SENSORS AND PROCESSES

> Data Fusion - a multi-level, multi-faceted process of dealing with the association, correlation, and combination of data and information from multiple sources to achieve refined position and identity estimation, and complete and timely assessment of situations and threats as well as their significance. [Ref 5:p. 6]

The sources and characteristics of data result in distinguishing between positional fusion and identity fusion. While many of the basic processes are the same, identity fusion requires a larger knowledge base and inferential reasoning techniques. The scope of this discussion is primarily on positional fusion.

A. POSITIONAL FUSION

Positional fusion deals with the kinematics of an object. Motion parameters, apart from mass and force are managed in this context. This includes position in three dimensions, motion vector (comprised of velocity, and bearing in three dimensional coordinate system), and velocity or bearing changes. Some of this information is received directly from sensors, while other parts of it must be derived. The challenge of positional fusion is to match sensor inputs with each other and with existing tracks in the database through mathematical and statistical manipulation of the raw data received from the sensor.

1. Sensors - The Information Source

Modern war fighting is as integrally dependent on sensors as it is on the weapons. The target must be located first using some kind of search mode. In order for a track to be established and maintained, the sensor must continue providing updated information at a rate high enough to ensure association ambiguity does not occur.

a. Sensor Types And Terms

Radar is the primary sensor for detection of targets on and above the surface. The measurements that can be obtained when using radar are the actual return or cross-section, and its transform in the frequency domain. This gives the user a signature which may be compared to a database for identification. Range, azimuth and elevation can be derived and in some cases target size and shape. From this and subsequent measurements, the position, velocity, and heading of the target can be determined.

Electronic intelligence (ELINT) receivers and electronic support measures (ESM) equipment provide signal amplitude and frequency at a specific time. Associated information are the signal to noise ratio, polarization, and pulse shape. Depending on the characteristics of the specific signal received, derived information might include target position, velocity, and identification. Characteristics of many EM emissions are well documented resulting in high probability of identification when detected.

Electro-Optical systems gather picture elements, electronically differentiating color and intensity. Although processing time is long compared to other sensor types, size and shape from the color picture can make identification possible.

Infrared provides similar data to the electro-optical, but in a different frequency range. Identification is possible, because information gathered can include location, size, shape, temperature, and other spectral characteristics. Position and velocity information are less determinant as they are generally dependent on the platform operating the IR sensor.

Communications intelligence (COMINT) may seem an unlikely "sensor" in this context, but it illustrates the complexity of fusing disparate data. In addition to signal analysis which can provide valuable information about the identification and location of the transmitting platform, the text of received conversations can reveal additional intelligence critical in understanding the intentions and tactics of the enemy. [REF 6:pp. 19-20]

To understand the strengths and weaknesses of each type of sensor it is important to be familiar with the basics of sensor characteristics. A few of the more important terms are defined in Table 1.

Radar with millimeter wavelength has high detection probability good ranging capability, but marginal angular resolution. It is not highly sensitive to weather and provides a low technical risk sensor. Electro-Optical sensors are passive (good in EMCON environment), high resolution and low technical risk, but they are limited by a light source, have difficulty providing target range, and are highly sensitive to weather. IR devices respond much better in inclement weather, and depending on the platform from which they are operated, may provide ranging. Though only a moderate technical risk and relatively undetectable, they must become active to provide target ranging.

b. Applications

In the air-air environment, the operator is intent on detection, tracking and if and identifying other aircraft. This includes a determination of friend or foe

TABLE 1
SENSOR TERMINOLOGY DEFINED [Source: REF 2:pp. 19-20]

TERM	DEFINITION
Spatial/Temporal Resolution	Ability to distinguish between two or more targets in space or time.
Spatial Coverage	Spatial volume covered by the sensor, for scanning sensors this may be described by the instantaneous field-view, the scan pattern volume and the total field-of-regard achievable by moving the scan pattern.
Detection/Tracking Modes	Search and tracking modes performed: 1. Staring or scanning. 2. Single or multiple target tracking. 3. Single or multimode (track-while-scan/stare).
Target Revisit Rate	Rate at which a given target is revisited by the sensor to perform a sample measurement. (Staring sensors are continuous.)
Measurement Accuracy	Accuracy of a sensor measurements in terms of statistics.
Measurement Dimensionality	Number of measurement variables (range, range rate, and spectral features) between target categories.
Hard/Soft Data Reporting	Sensor outputs are provided either as hard-decision (threshold) reports or as preprocessed reports with quantitative measures of evidence for possible decision hypothesis.
Detection/Track Reporting	Sensor reports each individual target detection or maintains a time-sequence representation (track) of the target's behavior.
Detection Performance	Detection characteristics (false alarm rate, detection probability, and ranges) for a calibrated target characteristic in a given noise background.
False Alarm Rate	Rate at which a detection is made in error.
Miss Rate	Rate at which sensor failed to make a detection.
Detection Probability	Probability of making a correct detection (sum of false alarm rate, miss rate, and detection probability rate is one).

possible aircraft type. To accomplish this sensor employment includes multi-mode radar (including IFF), infrared, electro-optical, and ESM.

For the ground attack mission, the goal is to search, acquire and identify hostile ground targets. Engagement and weapons control and damage assessment follow. Important to this mission are terrain-following radar, imaging/mapping radar, infrared detection, electronic support measures, and electronic countermeasures, and electronic counter-countermeasures.

The surface vessel is concerned about the air threat, and in its defense conducts surveillance for air traffic control, hostile target detection and identification. Tracking and engagement of hostile air threats follows. Air search radar (including IFF), fire control radar, electronic support measures and infrared detection are used to accomplish this mission.

The surface and sub-surface threat to the surface force requires surveillance of both media for detection and identification of targets. Support is also required to coordinate engagements between own force and the hostile. Typically employed are surface search radar, hull-mounted sonar, towed-array sonar, and electronic support measures.

In most of the threat scenarios, Airborne Warning And Control (AWACS) supports own forces with surveillance, detection and tracking, air traffic control, and coordination of force sensor data through various communications links. [REF 2:p. 105]

2. Fusion Processes

Alignment occurs first and is normalization of contact data or tracks to a common time and space reference. Next the target data must be associated with other target data being received and with track data already identified in the database. Tracking describes initiating, updating or deleting a track in the database. Initiation occurs when a contact is deemed to be a new object. An ID is assigned and a history file started. Update is a generic term to describe any one of many algorithms which statistically determine what effect new data has on an existing track, and mathematically append the history file to reflect the change. Deletion takes place when a track is no longer determined to be likely (statistically speaking).

a. Alignment

> Processing of raw sensor data to achieve a common time base, a common spatial reference, common units, etc., as necessary to properly normalize the data for subsequent processing. [REF 5:p. 1]

The first thing that must occur when a report is received, is normalization. To compare target reports with each other, regardless of the source of the raw data, they must be in the same time-space coordinate system. For organic sensor data, only the time associated information must be altered, as the position reference for the sensors is the same. This will require a mathematical manipulation of the position of the target based on kinematic features like bearing and velocity. For non-organic data, both the time of the report and the location of the original sensor must be considered in the process. [REFS 2 and 7]

b. Association

> The definition and calculation of a closeness metric on which the assignment of sensor data items to entities will be decided. The process of generating, scoring, and deciding on hypotheses about the question of which detection or measurements under consideration refer to the same object (come from the same target and should be associated) and which refer to different objects. [REF 5:p. 2]

Association employs mathematical and probabilistic algorithms for hypothesis testing. In its simplest form target track data is received from a shipboard radar, and must be matched with target track data existing in a database maintained on the same vessel. Important elements in the comparison are position, position accuracy, velocity, velocity accuracy, current bearing, and update time. Accuracy is a probabilistic value designated to each sensor. The received position must be evaluated against other positions on file to determine if it is a false alarm, existing target, or new target. In a low volume scenario, the new target data could be compared against every element of target data on file in a search for best fit. As a combinatorial problem, however, the amount of processing grows immensely in a target rich environment. To reduce the number of evaluations that must be processed at that degree of accuracy, a hierarchical process of elimination is used called gating. A gate test might be designed to compare just the velocity of a target. If the difference between the new target velocity and the velocity of a target in the database is greater than a specified threshold, then that target in the database is not further considered as a candidate for association with the new data. The same kind of gating is also done with position and bearing. Similar processes are used to reach association decisions with ESM, IR, and Electro-Optical data.

In the classical approach, Figure 3, association and estimation are separate and distinct processes. Kinematic data is first aligned as described above. The association process then pairs the actual data element with predicted (estimated) data elements from the database. The number of pairs is minimized by gating the kinematic data from the database, allowing only reasonable data to be used to form association hypotheses. The pairwise associated hypotheses are scored based on statistical distance between the actual and estimated pieces of data. These statistics might be probabilities of target existence, track length, or track sequence. If prior knowledge is available about any of the hypotheses, an a posteriori probability can be computed. The recursive process of generating and scoring the hypotheses will end with one (hard association decision) or more (soft association decision) hypotheses rewritten to the database. A track ID must be assigned to each hypothesis. In the classical model, the current target kinematics and an estimate of its future is written to the database as part of the track. The estimator uses the prior knowledge about the target based on the track dynamics and forms a model to estimate the kinematics for the next interval at which gating and association is expected to occur.

An adaptive approach to the association and estimation process, Figure 4, has been designed to more tightly integrate the two functions. Alignment occurs in the same manner, but selection of candidate tracks for association is made immediately based on distance criteria between the old target information and the new piece of data. Estimation is done on only those selected candidates aligning them in time to the new data. Gating is performed to eliminate unlikely candidates further minimizing the

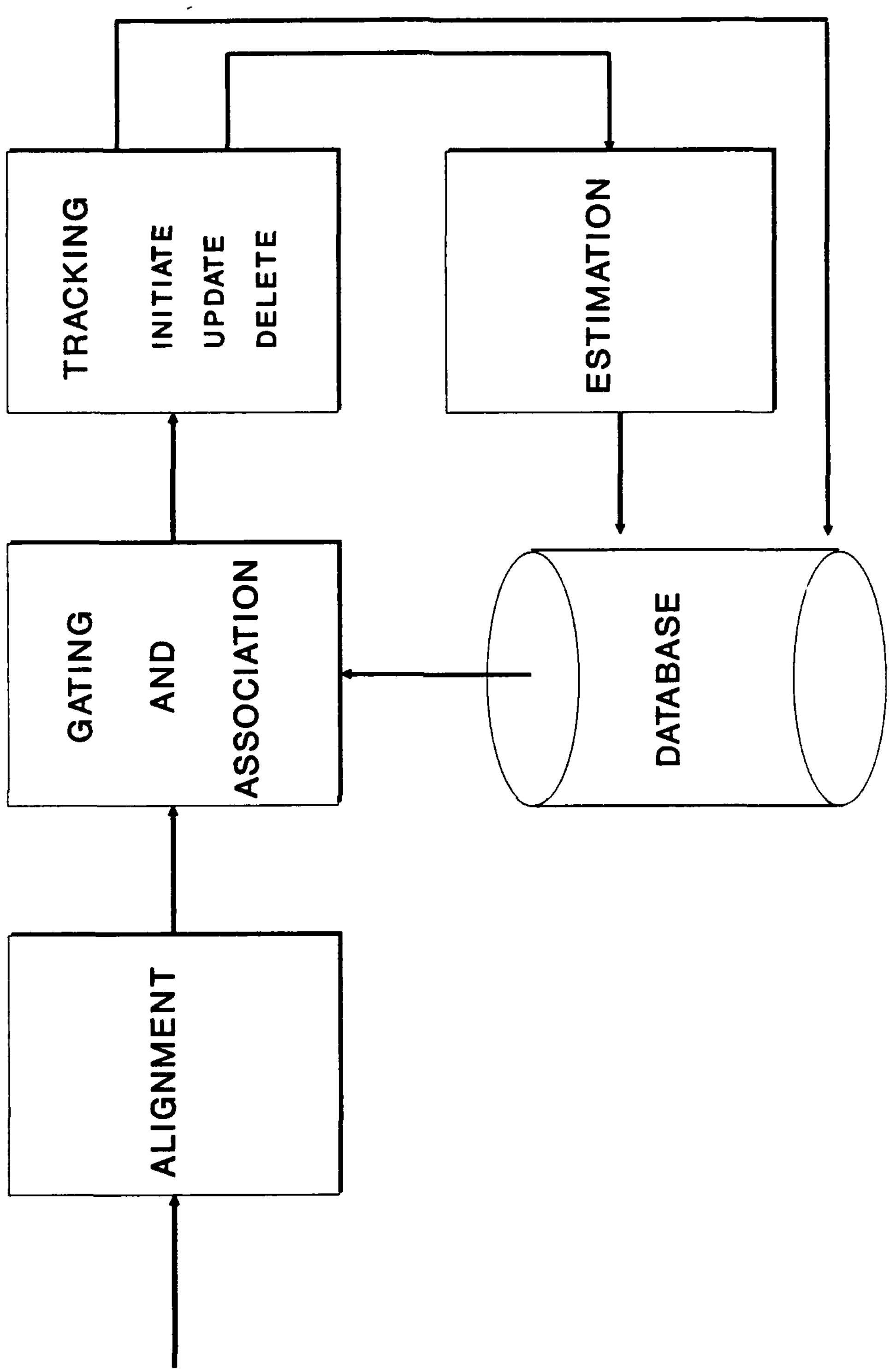

Figure 3
CLASSICAL ASSOCIATION ALGORITHM

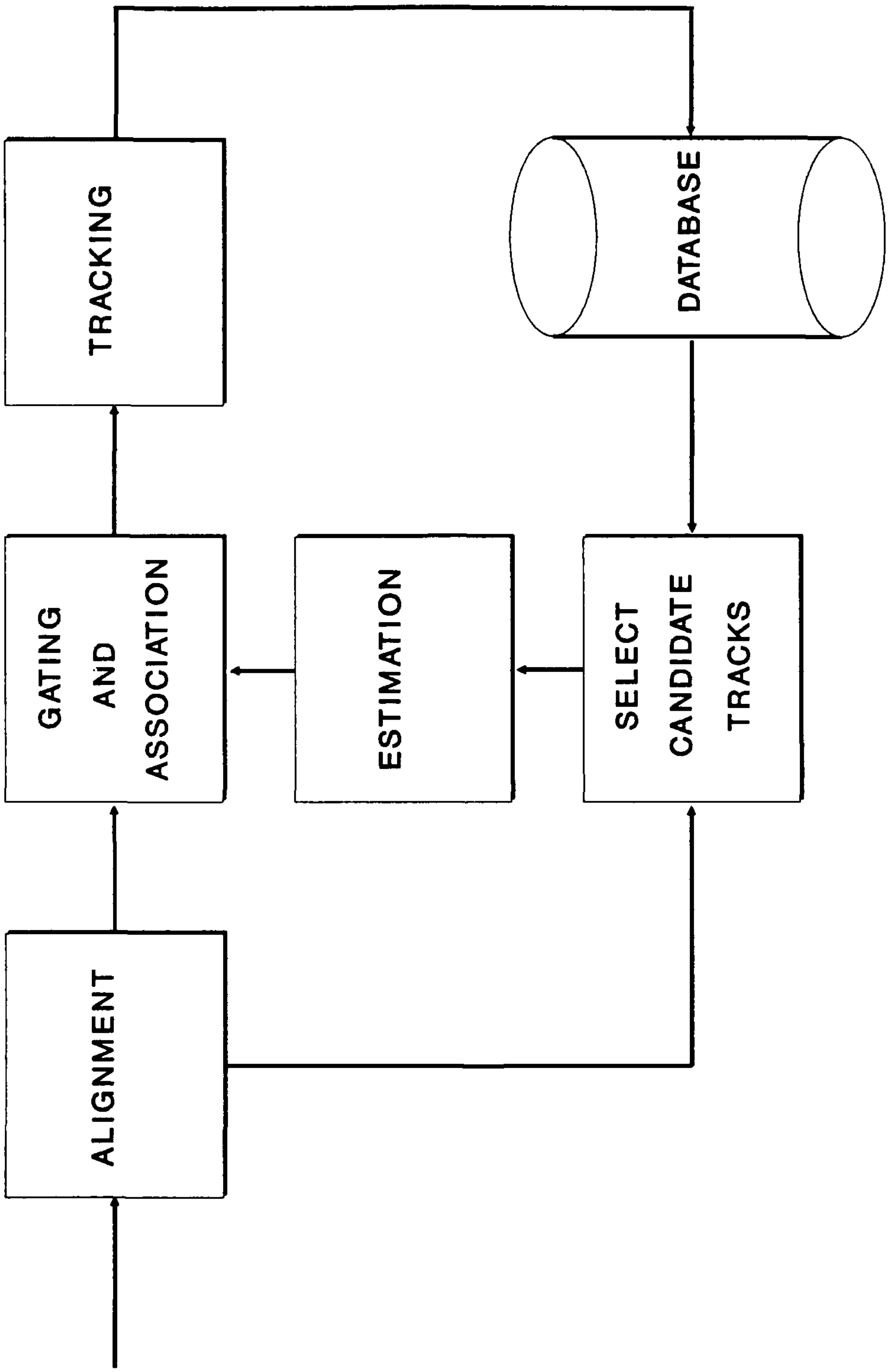

Figure 4
CONTEMPORARY ASSOCIATION ALGORITHM

number of association hypotheses. Hypothesis generation and scoring occurs in the same manner as the classical approach and after ensuring a track ID is assigned to each track, they are written to the database. Estimates of future kinematics are not maintained in the track database due to processing time and storage space constraints. The important ingredient in command and control, future prediction, is managed at the next level, situation assessment.

Complexity is induced when data is not from organic sensors. Questions of design arise which must be resolve. Is the information received raw or preprocessed data? If raw data, how is accuracy determined with respect to organic sensor data? If preprocessed, is there enough track information to make an accurate evaluation against existing data? Should it be evaluated against processed data only, or can it be compared with other raw data? Ultimately, association with an existing target in the database allows maintenance of a target history and estimation of future target position and kinematics. This is critical in target tracking. [REFS 2 and 7]

c. *Tracking*

> Precise and continuous position-finding of targets by radar, optical, or other means. [REF 1: p. 374]
>
> The computational process dealing with the estimation of an object's true position based on noisy observations (measurements) of it. Tracking may consist of filtering (estimating the position at the time of the latest observation), smoothing (estimating the position at a point in the past), and prediction (estimating the position at a point in the future). [REF 5:p. 13]

As comparisons are made between each data element, hypotheses for a match are generated. The probability of each hypothesis being correct is calculated and the tracks are updated based on the algorithm in use. If a soft decision approach is being used, several tracks may be updated for a period of time, until the system can determine which one is the correct track. The subject of multiple target tracking has been thoroughly researched and provides much of the foundation on which the mathematical processing is done for data fusion. While it may seem that solving the problem of tracking is synonymous to solving the problem of data fusion, it is not the case. In its simplest form, a target tracker is receiving sensor data from one source, like a radar. At each sweep, new information is received by the tracker. This must be evaluated against information received during the last sweep to determine if returns from different positions imply a moving target, or a new stationary target. The problem of tracking employs one or more of several mathematical processes or models. These include the Kahlman filter, probabilistic data association (PDA) and joint probabilistic data association (JPDA). [REF 8]

B. IDENTITY FUSION

Target recognition is categorized as identity fusion rather than positional fusion. Methods employed to accomplish this fall into three categories: physical models, parametric classification, and cognitive-based models.

In some cases, the identity of the target can be determined from analysis of electronic emissions. This requires a knowledge base of target characteristics including a template or inference modeling capability. When the signal of a radar, known to be employed on a specific type of aircraft, is received from an object, and other sensor inputs support the hypothesis (object airborne operating at a velocity within specified tolerance), the system can proceed, designating the target as that specified aircraft type. The knowledge base on that aircraft type will also provide the decision maker additional information about its threat capability.

Targets operating in more stealthy modes emit fewer obvious clues requiring the decision maker to analyze input from multiple sources. Sensors geographically separated can give two additional information features: earlier acquisition time due to proximity of sensor and a larger backscatter cross-section due to location of sensor relative to target track. A missile approaching the sensor platform directly will have a small cross-section, making it difficult to acquire until it either begins emitting a homing signal or gets too close. A sensor platform that is not along the flight path of the missile might be able to acquire and identify quickly, and relay the data to the first platform. Fusion allows the data from the geographically separated sensors to be merged, permitting earlier identification of the threat. [REF 2:pp. 214-217]

V. ARCHITECTURAL ALTERNATIVES

Pure centralized and distributed approaches to solving the problem of track management represent the endpoints of architectural design in the context of this discussion. A pure centralized system would receive data from all sensor platforms and process it at one site, sending the results back to the decision makers. At the opposite end of the spectrum, a distributed system would require the platforms to process all data which would be broadcast over a communications network. With this data each platform would build a situation assessment. Along the line between the extremes lie numerous hybrid approaches. A hybrid design utilizes both centralized and distributed processes in the system solution. Four designs are discussed in this research, the endpoints and two hybrid representations. They are not meant to be the final word on fusion system design, but rather to provide a platform for discussion of the architectural features which make design difficult. The four designs will provide a forum for a discussion of performance evaluation using the Analytic Hierarchy Process.

A. CENTRALIZED DESIGN

The central fusion processor, Figure 5, receives sensor data (contacts) from all sources and executes the fusion process as described in the previous section. Fused tracks are assigned an ID and maintained in a central database. The added value provided by multiple sensor contacts and multiple target perspectives makes the fused tracks more accurate. Track ID ambiguity does not exist because they are assigned at

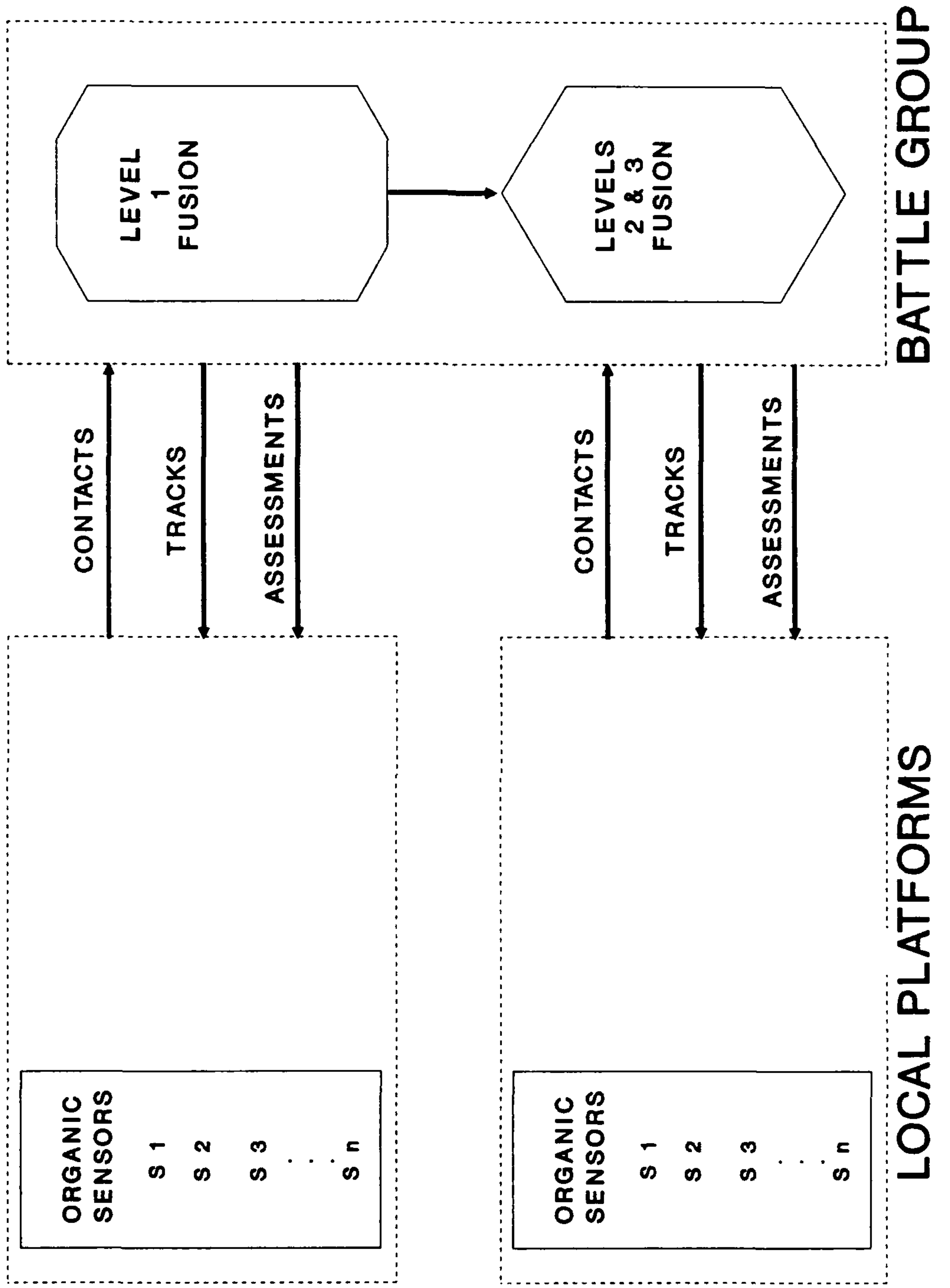

Figure 5
CENTRALIZED FUSION ARCHITECTURE

a single point. Situation and threat assessment is done at the battle group level incorporating the track data from the central database, as well as warfare doctrine, other intelligence information, and mission requirements (orders). The battle group decision maker interacts with the information, in the development of a composite tactical picture of his environment. This single composite picture is made up of targets being tracked by all platforms and assessments by the battle group. It is maintained in real time at the battle group level and broadcast to decision makers at all levels. Access to the raw sensor data at the platform level for command and control is denied.

B. DISTRIBUTED DESIGN

In the distributed approach, Figure 6, fusion is accomplished at the local platform level. Fusion occurs in the same fashion as described before, and the databases described in the central approach are the same, but they are maintained on each platform. Locally fused tracks are broadcast to all other platforms providing the added value of multiple perspective sensor data. Situation and threat assessment are performed at the local level in an automated process and relayed to the battle group commander for information. Since all platforms have the same sensor data available to them (except for minute differences in time of receipt of the data), and fusion processing occurs using the same algorithms, the resulting assessments are fundamentally identical for each platform decision maker. (This assumes that the assessment processes are automated. When human decision makers are doing assessments, they will be different in spite of identical data input.) Any differences are resolved by the battle group decision maker through

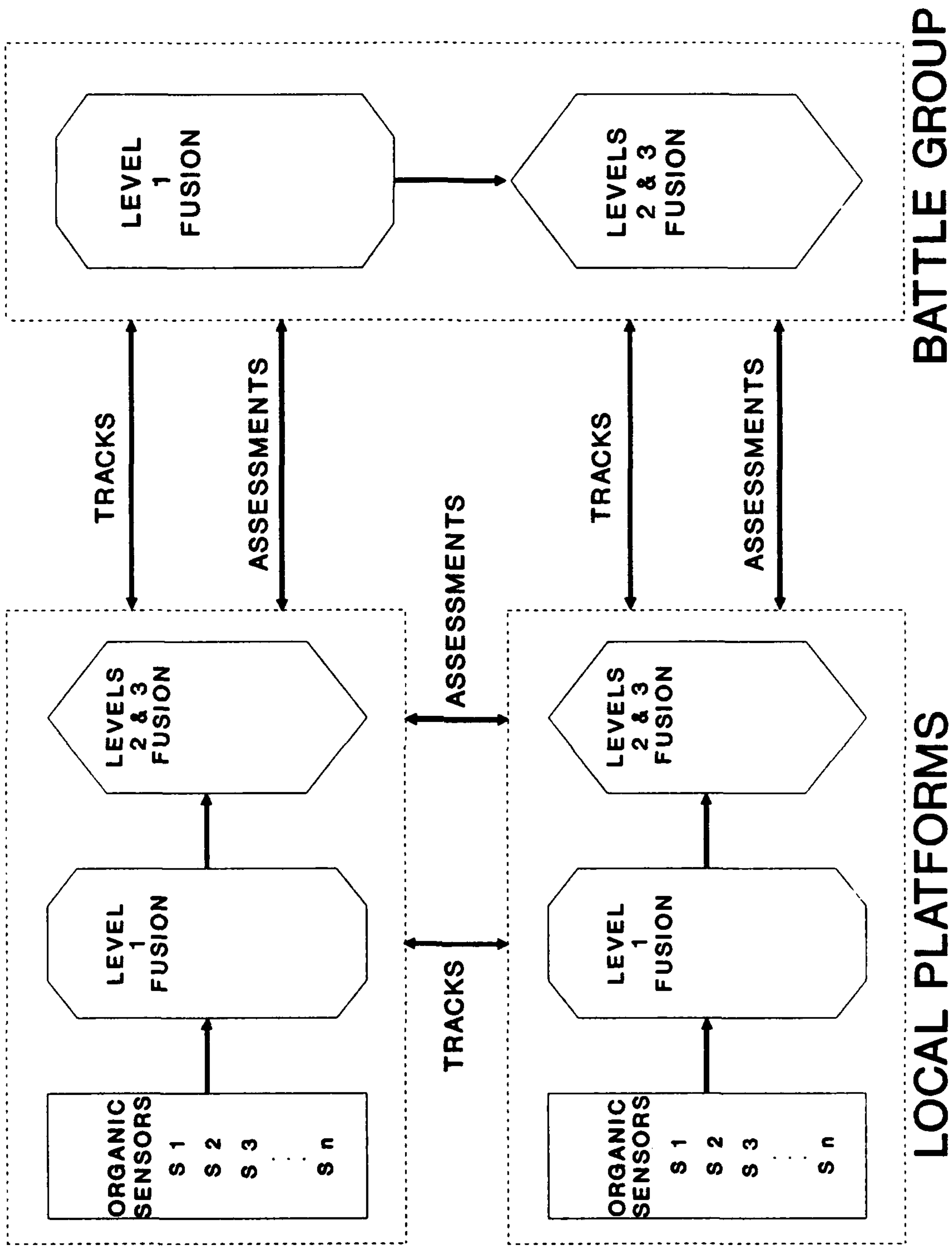

Figure 6
DISTRIBUTED FUSION ARCHITECTURE

updates to the doctrine, intelligence and operational orders. Real time target data management is enhanced, because while delays may occur in the broadcast of nonorganic data, the delay for processing organic detections is minute.

With respect to track ID numbers at the local level, tracks will have an ID's assigned at the local platform regardless of the source of the data. When track data is shared between platforms, ID's are ignored, because the fusion process that will occur on the receiving platform is only concerned with the kinematic and identity information in the track. Once association has been accomplished, that new track data will become part of an existing track or it will be assigned a new track number by the receiving platform. The battle group will manage track ID's in much the same fashion. Data management between platforms will take place apart from ID numbers.

C. HYBRID DESIGN (ONE)

Two hybrid models are considered. The first approach, Figure 7, closely resembles the quasi-manual system currently in use. Organic sensor data is processed and fused on the platform and a database of tracks is maintained locally. Information is passed between platforms and from other nonorganic sources in the form of tracks. These are fused with tracks in the local database using the same general fusion processes (manually executed for the most part). The responsibility of managing track ID's between platforms is accomplished by the assignment of blocks of numbers to each platform and the battle group level. If another platform has information that will add value to an existing track, or identifies a new track, it initiates the track using one of its

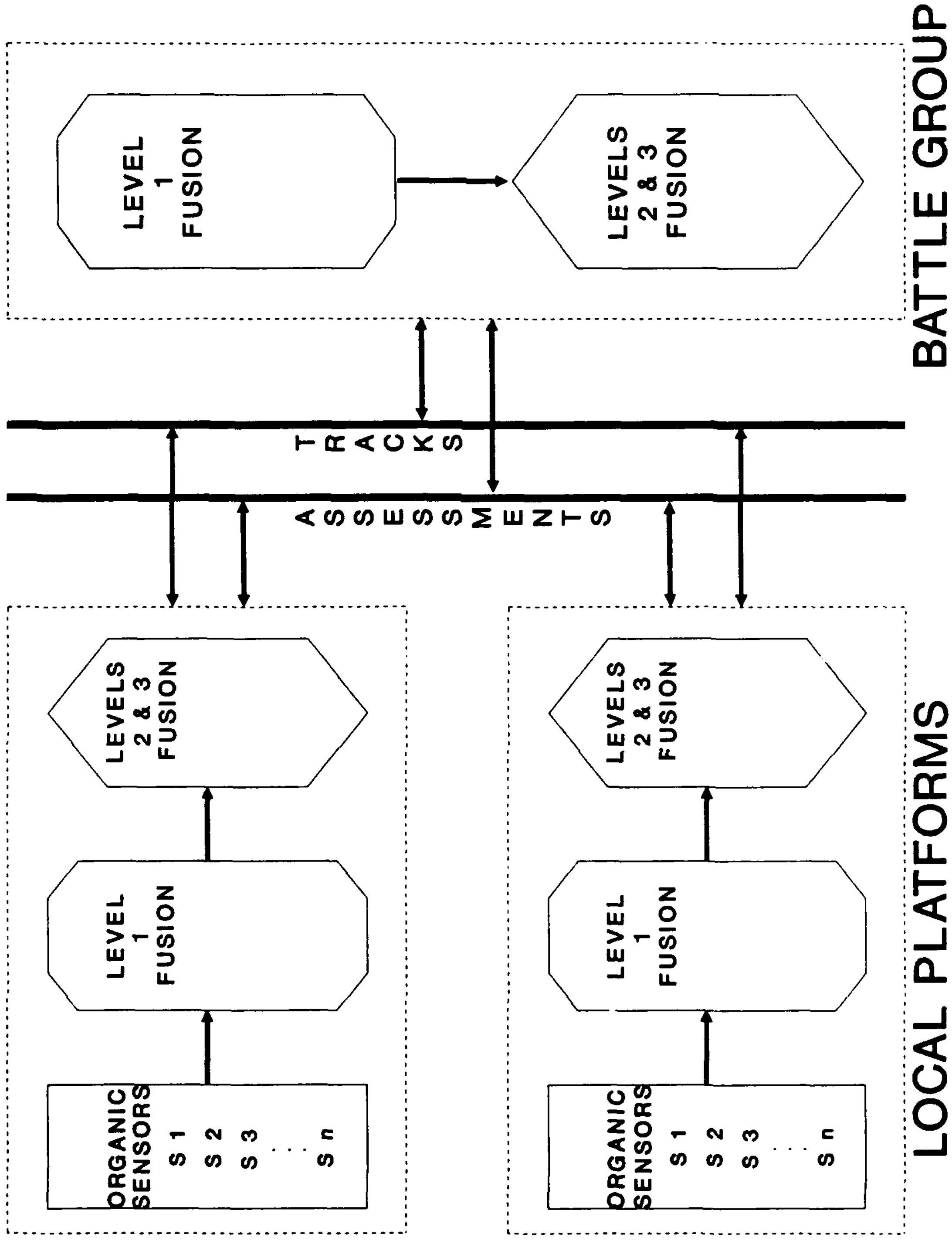

Figure 7
"HYBRID ONE" FUSION ARCHITECTURE

ID numbers and shares the data with other platforms and with the battle group level. The picture provided by the organic sensors and the shared data is used by local decision makers for tactical operations and assessments. Not only are the tracks shared in this architecture, but assessments as well. Functionally, for example, one of the platforms might have equipment which enhances its ability to process underwater targets. The tracks and assessments provide useful information to all platforms. The battle group decision maker accomplishes his own fusion, (a step which would be redundant if the processes were automated on all platforms), and analyzes it further for a higher level assessment.

D. HYBRID DESIGN (TWO)

The second hybrid approach, Figure 8, requires fusion at the local level, but situation and threat assessment at the battle group level. Multiple sensor contacts are received simultaneously and pairwise compared generating statistically scored hypotheses. The resulting tracks are forwarded to the battle group level for further processing. As multiple platforms operating in the same region forward track reports to the battle group fusion center, the tracks are pairwise compared, the hypotheses are statistically scored, and the fused tracks are assigned ID's. The fusion process at this level also requires comparison with tracks existing in the battle group database which were received previously from the platforms, or received from sources external to the battle group. The fused tracks with ID's assigned by the battle group fusion system are returned to the local platform along with a situation assessment. The same assessment is used as the

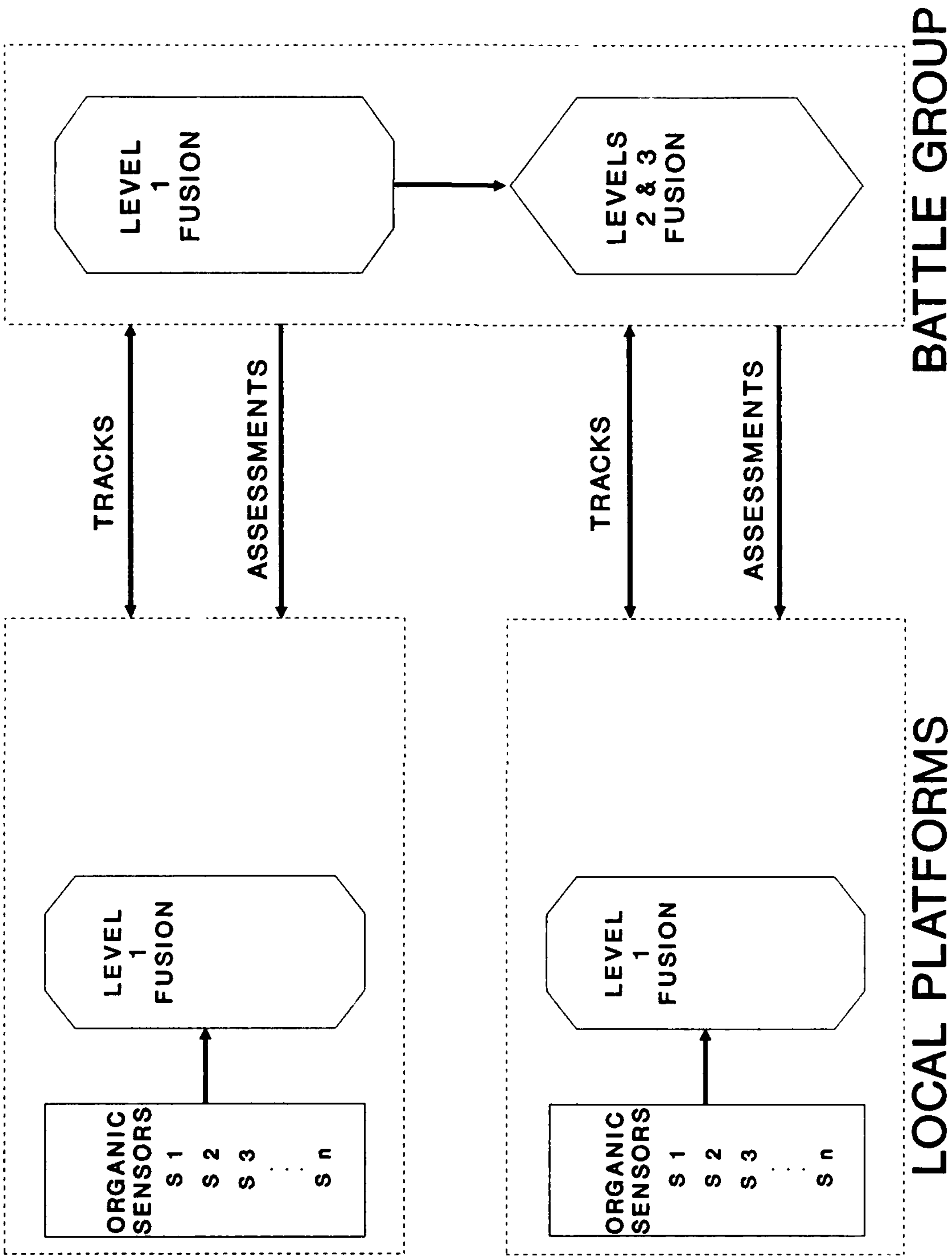

Figure 8
"HYBRID TWO" FUSION ARCHITECTURE

basis for decision making by all platform decision makers and by the battle group decision maker. The primary distinguishing feature of this architecture is in the minimization of required processing at the local level. Situation and threat assessment are done only at the battle group level because, in an automated system they require large databases and processing power. Replicating these processes on all platforms would be costly in terms of initial investment and maintenance.

VI. COMPARATIVE ANALYSIS

An comparison of the alternative architectures requires a discussion of design tradeoffs and performance evaluation. Many aspects of design could be mentioned, but most fall outside the focus of this research. The discussion of tradeoffs takes a more general look at the four designs previously described identifying strengths and weaknesses, but making no attempt to quantify them. The performance evaluation will attempt to identify measures of performance for a quantitative comparison of the designs. The Analytic Hierarchy Process will be employed, to demonstrate how alternative architectures could be compared.

A. DESIGN TRADEOFFS

Tradeoffs exist between the architectural concepts described here. The centralized fusion approach insures that no redundancy occurs in data management. No chance is given for duplication of track ID's between platforms. All decision makers are looking at the same tactical picture, and the same situation and threat assessment. On the other hand, the interval between detection and situation assessment is increased by propagation delay in data exchange resulting from the geographical separation of the two processes. While this may not affect routine intelligence analysis, the delay of a real time response to an missile threat could be fatal.

Distributing the processes insures a very short interval between local detection and situation assessment. It gives the local decision maker complete control over data from his organic sensors, but allows the added value of nonorganic data to be considered. This insures the decision maker has the most accurate track data available, a critical aspect of responding to a real time threat. Track ID's are controlled at the local level where they are most often utilized. This guarantees cognitive continuity in the decision making process at the local level. The number of a track does not change every time its accuracy is updated, and the ID is not constantly reused for different targets. Communications between platforms about a target become more complex, however, since no one uses the same ID number for a specified track. Decision makers would have to be trained that their track numbers are unique to their platform, and that discussion of track numbers between platforms will result in ambiguity.

The first hybrid approach to the problem resembles the current status of fusion in the level of manual processing that occurs. Organic sensor data is fused locally and track ID's are assigned. Situation and threat assessment are accomplished on site also ensuring accurate timely decision making. Both assessments and tracks are shared between platforms to provide added value to the tactical picture of each decision maker. While organic sensor data is fused automatically, anything that is received from another source must be manually evaluated and fused. The advantages of local processing as discussed in the distributed architecture apply here also. The problem of information sharing is somewhat mitigated by the assignment of blocks of track numbers to platforms (in that no ID will be duplicated), and the role of the battle group fusion processor in resolving ID conflict . This, however, does not account for the problem of cognitive management of the data. More pronounced due to the manual nature of the processing is the problem of changing ID's that will occur when information is shared on the network. For example, the target designated #123 might become #128 when the battle group information manager determines that the target is being tracked by more than one platform. In the manual manipulation of data, the decision maker who is under the stress of battle will not be able to keep up with constantly changing ID's.

The technology of the threat has put manual processes at great risk of failure. Automated management of information sharing is essential to future success. The final hybrid architecture is designed to account for these changes in technology. Fusion of organic sensor data and nonorganic track data is accomplished at the local level. This information is available locally to manage real time decisions when this is necessary. For the most part, however, situation and threat assessment takes place at the Battle Group level after fusion of multiple platform track data occurs. This enhances the accuracy of the tactical picture and the assessment. The platform has the advantage of using real time organic sensor data for tracking the incoming missile threat, but the depth and breadth of a complete analysis of the unidentifiable contact. Track ID's in the shared picture are managed by the battle group fusion system to insure interoperability. The shared picture becomes the primary reference for command and control, to allow early prevention of enemy action that might lead to the need for use of the local platform database. If targets get through the warning and assessment net of the battle group command and control system local platforms will have to act autonomously, and this architecture gives them the tools to do so. No time will be available for information sharing until the immediate conflict is resolved.

B. MEASURES OF PERFORMANCE

Measures of performance (MOP) in this context are attributes that measures the performance of the system in an operational environment. Measures of performance could be evaluated in a variety of frameworks and still avoid the key research issues of this thesis, so parameters which directly affect the Track ID management in the centralized, distributed, and hybrid architectures must be identified.

1. Measures Of Performance

The author examined the architectures, evaluated the expectations of a performance evaluation and selected the MOP's identified in Table 2. The intent of the evaluation is to identify the architecture which performs optimally with respect to the MOP criteria.

TABLE 2
MEASURES OF PERFORMANCE

Technical Characteristics Accuracy of fused tracks Timeliness of fused tracks ID Ambiguity Reliability
Cognitive Requirements
Cost

Technical characteristics are attributes which describe the capabilities of the system, rather than individual sensors. The issue of accuracy is almost a moot point, but it must be discussed to set the stage for the other MOP's. While raw data accuracy is sensor dependent, the degree of accuracy increases as multiple sensors are brought to bear on a single target. Whether the focus is on positional accuracy, or on identity, more information is better in most cases. In all of the architectures defined above, fusion occurs at some level. In the case of the centralized approach, all contacts are processed at a single point providing the highest degree of accuracy. If fusion is done in a hierarchical fashion, error can be induced at each level, and while the final product may still be better than a single report, it is not as good as it could have been.

The key issue to managing real time fusion is timeliness. Delay can occur both in processing and in data relay between platforms. The fusion of large volumes of raw data, as in the centralized architecture, will result in greater delay than fusion of processed data in the form of tracks. The assignment of track ID's at a single location can result in delay. Relaying of data between geographically separate platforms always results in delay.

Ambiguity in any form is detrimental to command and control in war. The architecture employed will provide varying degrees of ID clarity in track management. Single ID used for more than one target, single target labeled with more than one ID and constantly changing ID's describe ambiguity in this environment.

Reliability, while not the primary focus of this research, must be considered in the design of a fusion system. An architecture that is unusable when communications are degraded, or EMCON conditions are mandated is less reliable than a system that can operate autonomously.

The second major category is the cognitive interface. While this research has not focused on human factors, the degree of cognitive interface with the track management process will be different in each architecture. It is the opinion of this author that the human is the weakest link in the real time management of target tracks. That being the case, the degree to which the decision maker must participate in the fusion and response process will greatly affect the performance of the system.

Cost of design is discussed in terms of processing equipment and secure high bandwidth communications hardware. If processing is done at a single site, the cost of processing hardware is reduced, but the cost of communications hardware increases. Fusion in a distributed environment requires multiple processors and communications equipment. Economies of scale may apply for hardware acquisition, but since all of the architectures require multiple components of either computer equipment or communications equipment, scale would not be a deciding factor. Hybrid architectures require large numbers of components of both kinds, but some savings may be made in processing equipment if Level Two and Three processing is not executed on all platforms.

2. Architectural Comparisons

The tradeoffs occur in implementation. The centralized architecture will provide highly accurate tracks. No error will be induced through repeated fusion. While processing delay will be relatively short (because all processes are executed only once), there will be a delay in the transfer of data between the platforms and the battle group fusion center. Since this architecture restricts local access to the raw data, the delay could be fatal if the platform was unable to react in a timely fashion to a real time threat. ID clarity receives high marks because all ID's are assigned at a single point. Associated with this, the cognitive participation of the human decision maker is low, enhancing the performance of the system. On the other hand, this may be an additional cause of delay since the platform cannot respond to any threat until the central fusion processor has received, processed, and returned the track information. Reliability is impacted negatively as a result of the communications essential design. With respect to affordability, this design requires the least in terms of processing equipment, but relies heavily on high speed communications hardware.

The distributed architecture ensures that tracks are accurate through fused tracks from the battle group center. Timeliness is impacted only with respect to the receipt of track information from nonorganic sources. There is a clear tradeoff between accuracy and timeliness in this architecture. On the other hand, each platform has fused tracks on site from organic sensors allowing it to respond to the real time threat. Clarity is managed through autonomy. While track numbers cannot be shared between platforms, the fused picture that each decision maker maintains should be fundamentally identical. Ambiguity may exist where platforms are operating close together in a high threat environment, if decision makers try to communicate about targets using track ID numbers. The human decision maker cognitive participation is greater in this environment with respect to interoperability with other platforms. As to affordability, processing equipment is required on each platform as well as communications hardware.

The system is more reliable. Even if communications are degraded, platforms have the ability to detect, track, assess, and respond to a threat.

The current manual system, described in the first hybrid design, must be compared on a different level. While the fact exists that fused tracks are more accurate, manual processing induces error and bias resulting in a track which may not be as accurate as the raw data. Compounding the problem is the inherent delays in the manual system. Error may be induced simply because track data received from other sources is old. Ambiguity is of key concern when manual processes are in place. Failure of the battle group level to manually detect a conflict will result in confusion at all levels. Cognitive processing occurs throughout the system impacting accuracy, timeliness, and ambiguity. Reliability and affordability are associated again, in that while the system is the most affordable (utilizing lower speed communications hardware, and manual processing), is the least reliable.

The second hybrid design attempts to provide a realistic solution, in terms of both cost and reliability. The local platform has the ability to respond in a timely manner to a real time threat, as well as utilize the added value of fused data. Control of ID conflict is managed by the battle group level reducing ambiguity while allowing autonomous operation when necessary. Cognitive processing requirements are reduced at the local platform level, and centralized at the battle group level. Data processing is reduced at the local level by moving all situation and threat assessment to the battle group level. The communications requirement for track management is full duplex, but assessment distribution is simplex or broadcast, making the design more affordable. The reliability factor limits the ability to access fused tracks from other sources when communications are degraded. The platform will be forced to rely on data from organic sensors. While this level of autonomy may not be desireable, tactical operations can still continue with the processing equipment located on each platform.

C. ANALYTIC HIERARCHY PROCESS

The Analytic Hierarchy Process is a decision tool which allows the user to structure problems into a hierarchy of interrelated decision elements. At the highest level is the single goal or objective the user is trying to reach. The user is attempting to make a comparison or selection of alternatives. Below the macro decision objective fall criteria that are used to evaluate each alternative. Each attribute is given a weight for importance or likelihood. Sub-attributes can be specified at a lower level with weights for each. At the bottom of the hierarchy each alternative is listed and a value is assigned which indicates how that alternative measures up to each attribute. The evaluation is somewhat subjective in nature, as a natural consequence of the fuzziness of the problem. The tool provides a means for assigning quantitative measures to problems that are not well defined. [REF. 9:pp. 96-101]

In the case of architectural comparisons as described in this research, a designer might use the following techniques to determine which is the optimal architecture. Measures of performance must first be identified, and their fit in each design evaluated. The next step is to structure the problem in a hierarchical fashion and assign weights to each attribute. In all of the steps where weights are determined, absolute values can be assigned or pairwise comparisons can be made between each of the alternatives resulting in relative weight values. The final step in the process is obtaining values for each attribute, measured for each architecture. These values might be subjective in the case of the cognitive requirements of the system, but cost and technical characteristics are quantitative values. Accuracy, for example, must be measured for each system and the results normalized to 1.00. For this illustration the values were all subjectively assigned by the author.

Figure 9 represents the structure of the problem, including the weights assigned to each attribute and the values "obtained" from each architecture. On the first level of attributes, cost was determined to be of lesser interest than the other two criteria. Technical characteristics were closely evaluated against the cognitive requirements of the system. The author judged that since the technical design drives the cognitive interface, its weight should be slightly higher. At the second level technical characteristics were broken down into accuracy, timeliness, ambiguity and reliability. The level of ambiguity was considered to be most important of these criteria. Accuracy and timeliness followed in that order. The accuracy attribute was judged to be more important because it was the focus of data fusion, while timeliness measured how quickly accurate information could be generated. The reliability factor was given the lowest value, because as a measure of how well the system would function under stress, it was considered of secondary importance in this evaluation.

For this illustration the measurement values for each architecture were assigned on the following basis. The Hybrid One (quasi-manual) system was judged the least

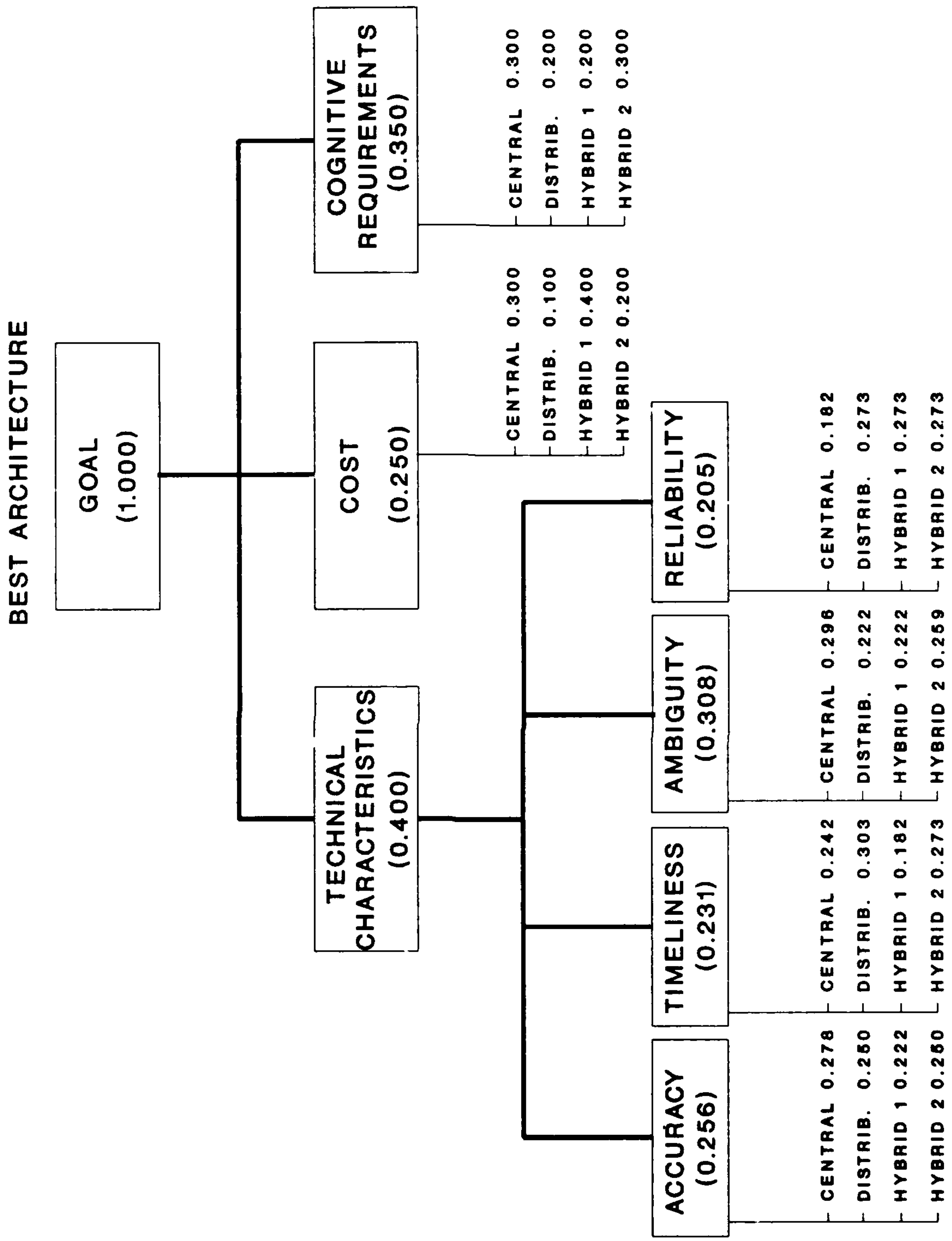

Figure 9
AHP PROBLEM STRUCTURE

expensive, as indicated by the high value assigned. A Distributed architecture, assigned the lowest value, was judged to be the most costly. The Centralized and Hybrid Two systems were considered to require low cognitive interaction, while the Distributed and Hybrid One demanded slightly higher interaction. The values assigned for the technical attributes follow the vein of the earlier discussion. The Centralized system is highly accurate and insures low ambiguity, but is less timely and not very reliable. The Distributed system is timely, reliable, and relatively accurate, but results in a greater amount of ambiguity. The Hybrid One design is low in all categories except reliability. The Hybrid Two architecture was assigned values for each attribute which placed it between the extremes.

Understanding that no particular solution was sought by the author, sensitivity analysis in this illustration provides some interesting insights into the attribute weight assignment process. Figures 10-12 are sensitivity plots for goal change with respect to each of the first level attributes. With the exception of the Cost attribute, Figure 10, the data ("measured" values) make a strong case for the Centralized architecture.

To illustrate the interactive analysis process, the author made changes to the weights in an attempt to change the "optimal" architecture. Since the weights must be normalized to 1.00, no single attribute can be changed. Modifications must be made to two or three of the attribute weights. The author reevaluated the systems holding the weight of each attribute fixed and changing the other two. With Cost fixed at .250, Cognitive and Technical Characteristics weight were altered in both directions, but there was no change in the selection of an optimal architecture. Fixing Cognitive requirements

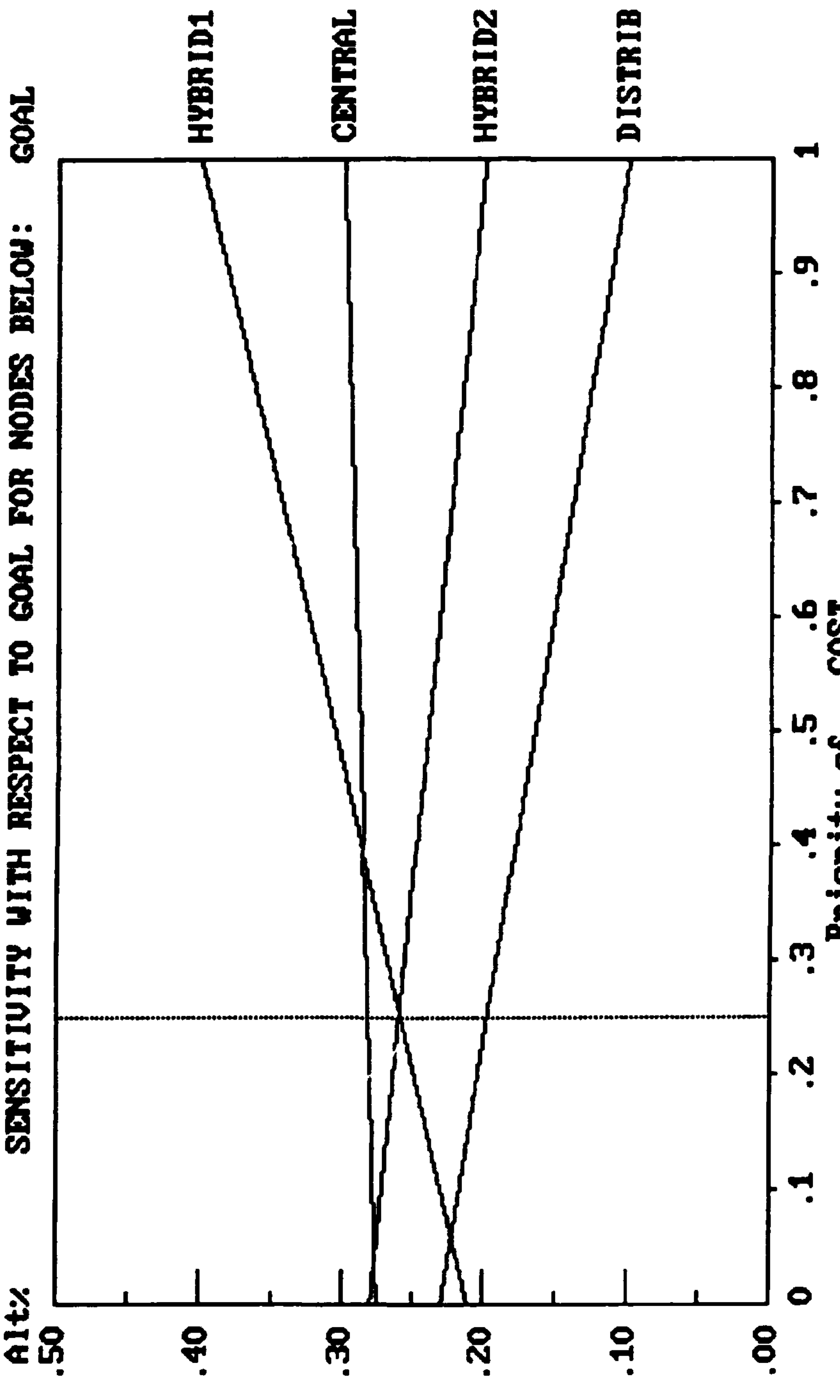

Figure 10
SENSITIVITY PLOT FOR COST

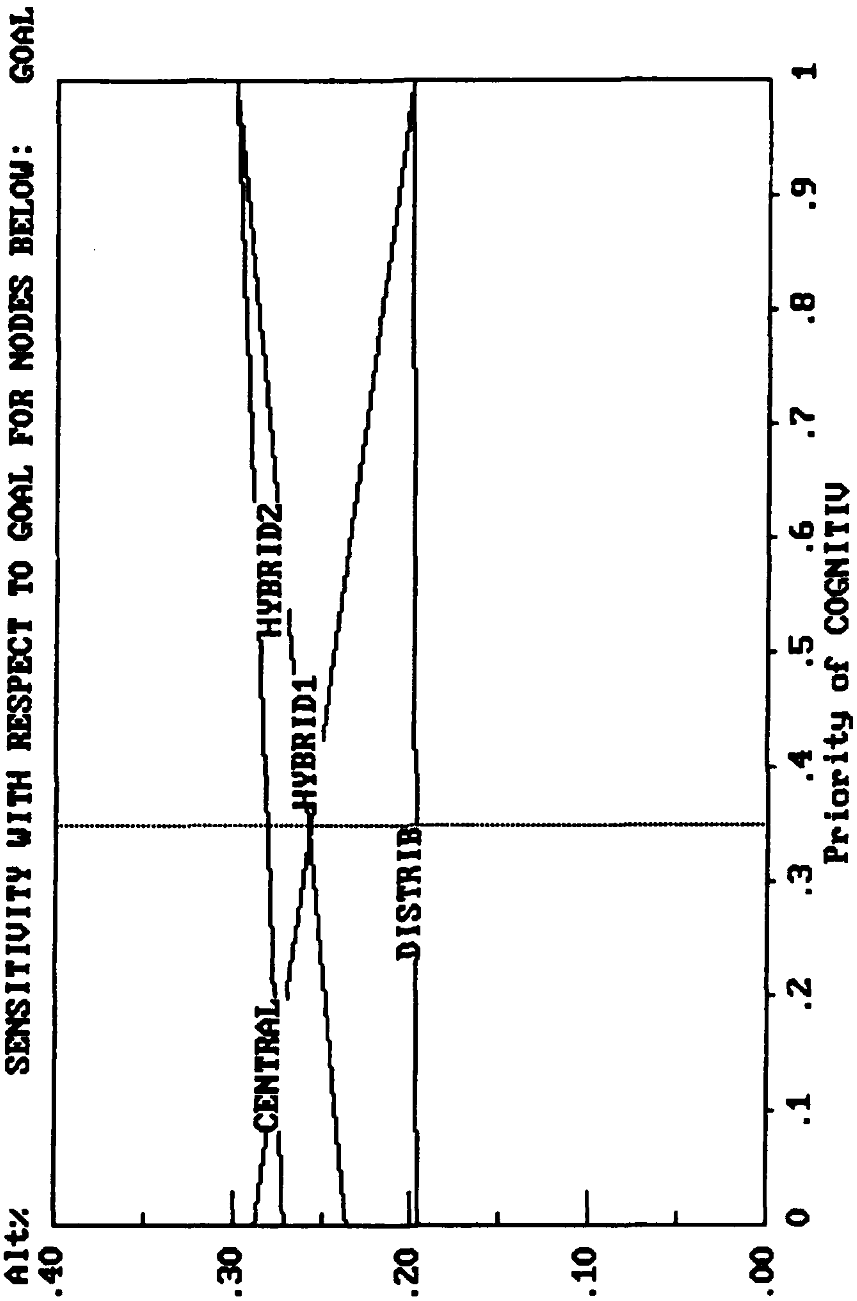

Figure 11
SENSITIVITY PLOT FOR COGNITIVE REQUIREMENTS

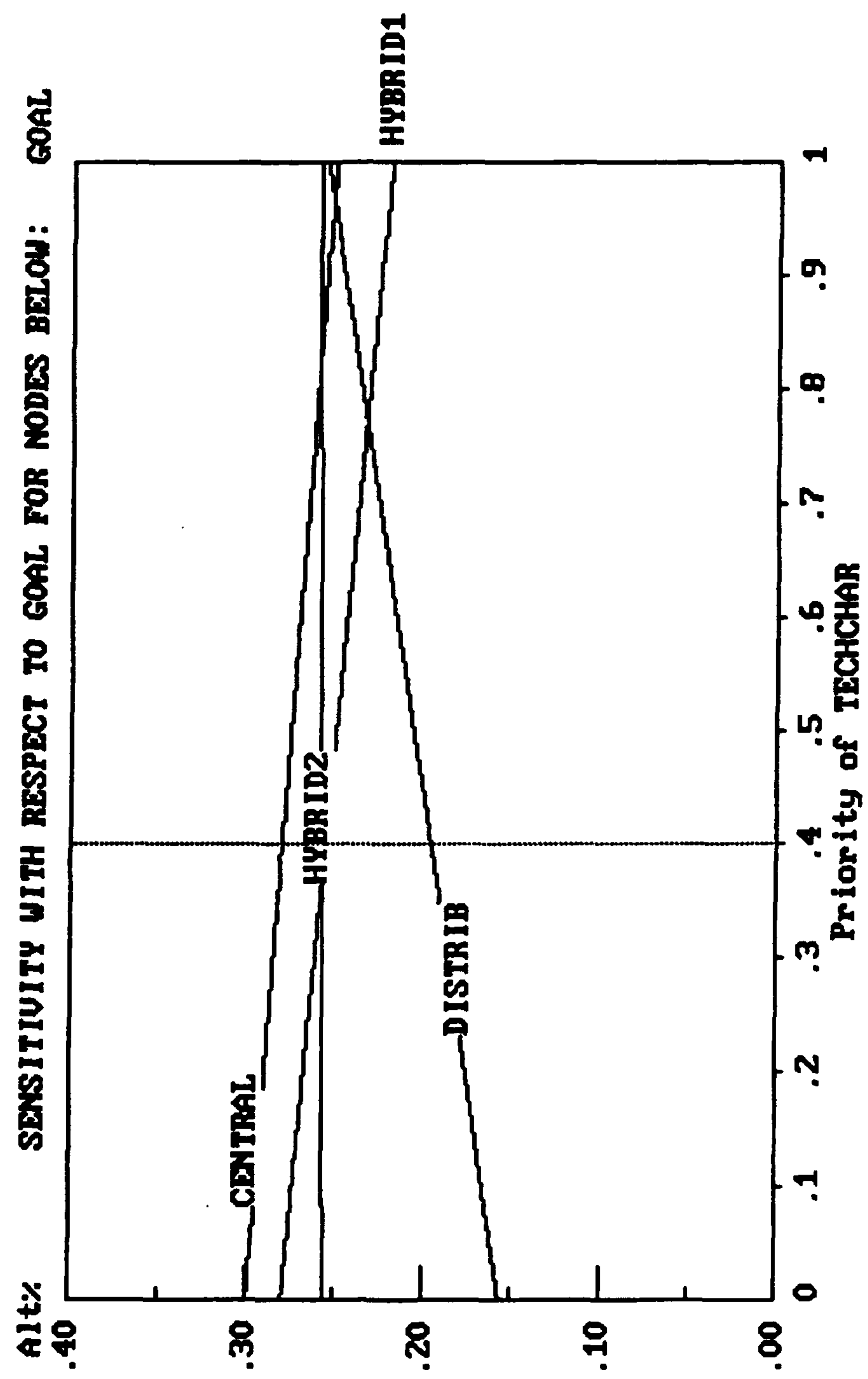

Figure 12
SENSITIVITY PLOT FOR TECHNICAL CHARACTERISTICS

at .350, the optimal architecture changed to Hybrid Two by reducing the weight of the Cost factor to .032 and increasing Technical Characteristics to .618. When the weight of the Technical Characteristics attribute is fixed at .400, Cost weighting needs only increase to .370 and Cognitive to .230 to change the optimal architecture to the Hybrid One.

This is an illustration of the process which must be used to evaluate architectural tradeoffs and select an optimal design. For an actual evaluation, the number and specificity of performance criteria should be increased. A more thorough analysis of the weights assigned to each decision element should be undertaken, and actual measurements would be used for each architecture.

VII. SUMMARY AND CONCLUSIONS

The author has described some of the problems associated with managing large volumes of sensor data for command and control. Data Fusion processes provide the tools for enhancing the accuracy of sensor information and assessments of the environment. Ambiguity in decision making remains the key problem which must be addressed. The process for building an architecture for C^2 Information Management using fusion has been described. Crucial in the process is identification of measures of performance and comparative analysis of architectural designs. The author illustrated a method for this evaluation using the Analytic Hierarchy Process.

While this research suggests that a centralized architecture will provide the most accurate, least ambiguous, and lowest cost design for data fusion, it is clear that the result is dependent on the "measured" values assigned to each architecture. Actual measurements must be obtained for a more conclusive decision. Since command and control increasingly requires knowledge of events far beyond the immediate operational theater, an evaluation should also include factors critical to the strategic decision making process.

The problem of managing track numbers will not go away. With greater information sharing it will become even more critical. To support information exchange to this degree and minimize track management ambiguity, a distributed fully inter-connected network of fusion centers should be designed. Shore and afloat facilities will provide the decision maker access to vital information outside his immediate purview while giving him complete control of information processing in the immediate vicinity. A virtual network with multiple protocol layers would allow the raw data to be accessed by any node on the network. At the same time, a higher layer could provide fused estimates of position and identity accessible to echelons who are either incapable of doing their own fusion or desire only the "big picture". The fully inter-connected environment minimizes, the problem of track ID management through system and interface standardization and process automation.

Modern warfare demands employment of technologically advanced weapons. Strategic in their success is information management. This can only be accomplished with faster and better decision processing, the elimination of unnecessary redundancy, employment of a fully connected communications environment, and greatly enhanced human interface designs.

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